New windows on massive stars: asteroseismology, interferometry, and spectropolarimetry
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Winds of metal-poor OB stars: Updates from HST-COS UV spectroscopy

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Abstract. In the race to break the SMC frontier and reach metallicity conditions closer to the First Stars the information from UV spectroscopy is usually overlooked. New HST-COS observations of OB stars in the metal-poor galaxy IC1613, with oxygen content ~1/10 solar, have proved the important role of UV spectroscopy to characterize blue massive stars and their winds. The terminal velocities (v_∞) and abundances derived from the dataset have shed new light on the problem of metal-poor massive stars with strong winds. Furthermore, our results question the v_∞-v_{esc} and v_∞-Z scaling relations whose use in optical-only studies may introduce large uncertainties in the derived mass loss rates and wind-momenta. Finally, our results indicate that the detailed abundance pattern of each star may have a non-negligible impact on its wind properties, and scaling these as a function of one single metallicity parameter is probably too coarse an approximation. Considering, for instance, that the [α/Fe] ratio evolves with the star formation history of each galaxy, we may be in need of updating all our wind recipes.

Keywords. Galaxies: individual: IC 1613 – Stars: early-type – Stars: massive – Stars: Population III – Stars: winds, outflows – Ultraviolet: stars

1. Introduction

Massive stars impact the dynamics and the energetics of their host galaxy both locally and at galactic-scale. They are also the claimed progenitors of two of the most energetic events of the Universe, long γ-ray bursts (GRBs) and some kinds of supernova (SN). Therefore a number of Astrophysics disciplines require understanding how massive stars live and die, and estimates of their multi-facet feedback.

The radiation-driven winds (RDWs) experienced by blue massive stars not only contribute to mechanical feedback but are also one of the principal agents of their evolution. By removing mass and angular momentum from the star, RDWs alter the physical conditions at the stellar core, the nuclear reaction rates, the duration/sequence of evolutionary stages, the ionizing fluxes, the yields and, eventually, the supernova engine.

Because the Universe is more metal-poor as we go back in time (e.g. Prochaska *et al.* 2003) and because the First Stars were likely very massive and roughly metal-free, the massive star community has taken an earnest interest in metal-poor massive stars. Even though the theoretical framework for as low as $Z \leqslant 10^{-4} Z_\odot$ already existed (e.g. Kudritzki 2002; Schaerer 2002) the Small Magellanic Cloud (SMC), with roughly $1/5\,Z_\odot$, stood as the reference for the low metallicity regime until recently. The theoretical predictions for low-Z winds and evolution were contrasted against observations of SMC massive stars, and their spectra were used to simulate metal-poor populations.

The advent of the 8-10m class telescopes, and in particular the instrumentation at the Very Large Telescopes (VLT) and the Gran Telescopio Canarias (GTC), have granted access to resolved massive stars in farther galaxies, hence opening the way to more metal-poor environments (Garcia *et al.* 2011). In particular, the spotlight is currently on the dwarf irregular galaxies IC1613, NGC3109 and WLM, where the oxygen abundance of HII regions scales to a global metallicity of $Z \sim 1/7\,Z_{\odot}$.

The problem of low-Z O-type stars with strong winds:
Because RDWs are powered by the scattering of photons by metallic lines they were expected negligible in galaxies with poorer metal-content than the SMC. However, recent findings suggest otherwise and have puzzled the community over the past 5 years.

Our VLT-VIMOS program on IC1613 revealed a luminous blue variable star with strong P Cygni profiles (Herrero *et al.* 2010), and an Of star whose wind lines suggest a stronger wind momentum than predicted by theory or a rare case of slow wind acceleration (Herrero *et al.* 2012, hereafter H12). Independently, Tramper *et al.* (2011, hereafter T11) studied a sample of O-stars in IC1613, NGC3109 and WLM with VLT-XSHOOTER, and found that their winds were also stronger than the prediction.

The results of these works have large error bars which add to yet unexplored wind inhomogeneity effects. However, the fact that almost all studied stars exceeded the theoretical prediction (see Fig. 1-left), and the large potential impact on the evolution and feedback of low-Z massive stars, granted renewed interest from the community.

2. Analysis of ultraviolet (UV) spectroscopy

H12 and T11 did not directly obtain the mass loss rate ($\dot{M}$) but the parameter Q=$\dot{M}/(v_{\infty}\cdot \mathrm{R}_{\star})^{1.5}$ (Kudritzki & Puls 2000). Lacking a value for the terminal velocity (v_{∞}), which can only be measured from UV lines, optical studies usually estimate v_{∞} from calibrations with the escape velocity which suffer from large scatter (v_{∞}/v_{esc}= 2.65, Kudritzki & Puls 2000), and then scale it with Z using the empirical relation $v_{\infty} \propto Z^{0.13}$ (Leitherer *et al.* 1992). This procedure introduces large errors into $\dot{M}$ that propagate to the WLR, the relation between the modified wind momentum ($\mathrm{D_{mom}} = \dot{\mathrm{M}} \cdot \mathrm{v}_{\infty} \cdot (\mathrm{R}_{\star}/\mathrm{R}_{\odot})^{1/2}$) and stellar luminosity, and our main tool to evaluate the wind strength.

The confirmation of the *strong wind problem* required UV spectroscopy to directly measure terminal velocities and improve mass loss rates and $\mathrm{D_{mom}}$. We obtained 23 orbits of Hubble Space Telescope (HST) to observe a sample of IC1613 OB stars (Tab. 1) with the Cosmic Origins Spectrograph (COS). The data cover with good signal to noise ratio the ~1150-1800Å spectral range, with a resolution of R ~ 2600. These are the first good quality UV spectra of OB stars in an oxygen-poorer galaxy than the SMC.

The terminal velocities were determined with the Sobolev plus Exact Integration (SEI) method (Lamers *et al.* 1987), using J. Puls's implementation of Haser (1995)'s code. More details on the observations and their analysis are provided in Garcia *et al.* (2014).

Table 1. Program stars and derived terminal velocities. ID numbers from Garcia *et al.* (2009).

	69217	62024	65426	67559	63932	69336	62390	60449
Sp. Type	O3-4Vf	O6.5IIIf	O7.5III-V((f))	O8.5III((f))	O9II	B0Ia	B0.5Ia	B1.5Ia
v_{∞}[$\mathrm{km\,s^{-1}}$]	2200^{+150}_{-100}	1250^{+150}_{-200}	1500^{+250}_{-250}	1500^{+300}_{-200}	1000^{+500}_{-400}	1300^{+100}_{-100}	1075^{+75}_{-75}	875^{+75}_{-75}

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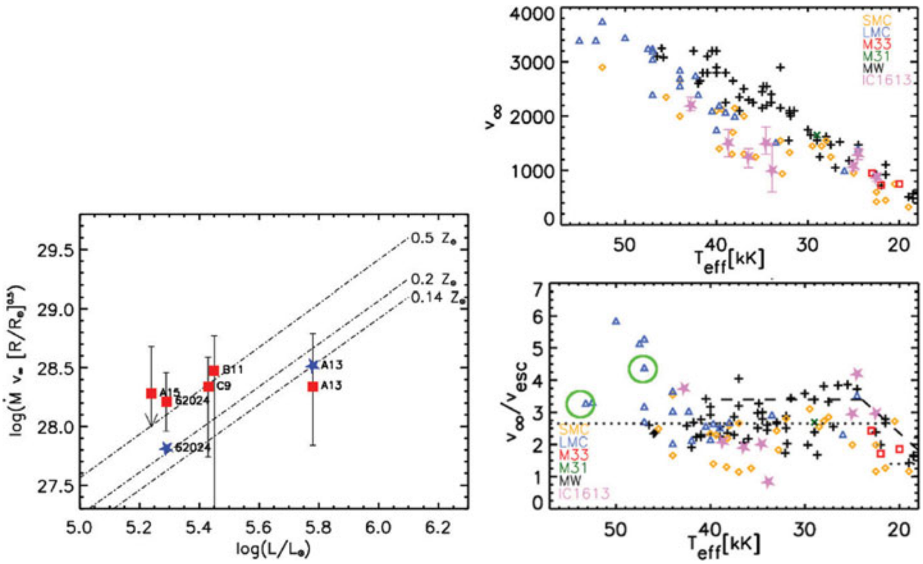

Figure 1. Left: The wind-momentum luminosity relation of IC1613 stars. Squares mark T11 and H12 results, and stars mark our updated values using UV terminal velocities. The dashed–dotted lines are Vink *et al.* (2001)'s predictions for the WLR at $0.14\,Z_{\odot}$, $0.2\,Z_{\odot}$ and $0.5\,Z_{\odot}$ (representing IC1613, SMC and LMC). **Right:** Terminal velocities (up) and the v_{∞}/v_{esc} ratio (down) of LG O- and early-B stars as a function of effective temperature (rhombus: SMC; triangles: LMC; squares: M33; crosses: M31; plus-signs: MW; stars: IC1613). The dotted lines mark the $v_{\infty}/v_{esc} = 2.65$ ratio, and the dashed lines the relations found by Crowther *et al.* (2006) and Markova & Puls (2008) for Galactic B-supergiants. The photospheric parameters of the two encircled targets were derived by Rivero-González *et al.* with the latest version of FASTWIND.

2.1. *Results*

The WLR revisited:

We recalculated the wind momentum of two stars included in the T11 and H12 samples with our derived terminal velocities. Their updated $D_{\rm mom}$ better matches the prediction for IC1613 metallicity (Fig. 1-left), illustrating the important role of v_{∞} to assess the WLR. We note that final $D_{\rm mom}$ values must await a consistent analysis that constraints photospheric and wind parameters, abundances and clumping, planned as future work.

The v_{∞} vs Z dependence:

We compiled all the terminal velocities of OB stars in Local Group -LG- galaxies derived from UV diagnostics, and their photospheric parameters derived by modern works (see Garcia *et al.* 2014, for references). Fig. 1-right shows a clear trend of increasing terminal velocity with increasing effective temperature ($T_{\rm eff}$). However, we detect no clear dependence of v_{∞} with host galaxy. IC1613, SMC and LMC O-stars are found in the same locus, whereas they clearly depart from Milky Way (MW) stars. This contradicts the prediction of a simple $v_{\infty} \propto Z^{0.13}$ relation: if MW 40000 K O-dwarfs have $v_{\infty} \sim 3000\,{\rm km\,s^{-1}}$, we would expect that LMC/SMC/IC1613 $Z_{\odot}$ stars have $v_{\infty} \sim 2740/2430/2220\,{\rm km\,s^{-1}}$. No segregation with metallicity is detected in the B-supergiant regime.

The v_{∞}/v_{esc} scaling relation:

The v_{∞}/v_{esc} vs $T_{\rm eff}$ plot shows no separation with metallicity, not even with MW stars. O- and B-supergiants cluster around the canonical $v_{\infty}/v_{esc} = 2.65$ value with some scatter, but the sample of LG dwarf stars exhibits large departures.

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v_{esc} is subject to several sources of error, some inherited from gravity (log g requires accurate $T_{\rm eff}$'s and a good nebular subtraction) and some, specially in the MW, from distance. Even though we only used photospheric parameters derived with the state-of-the-art codes FASTWIND and CMFGEN, the methodology of different research groups may also introduce some scatter. We note here two stars analyzed by the same team with the latest version of FASTWIND (Rivero González *et al.* 2012a,b) that properly treats the high-temperature regime. These targets, marked within green circles in Fig. 1-right, have v_∞/v_{esc}=3.3 and 4.4 hinting real departures from the wide-spread used 2.65 value.

The iron content of IC1613:

The morphological comparison of IC1613, SMC and LMC stars suggests that the iron content of the IC1613 sample stars is similar to, or even slightly higher than the SMC's. Moreover, the photospheric models that best reproduced the observed UV pseudo-continuum, dominated by iron lines, had SMC metallicity.

While pending confirmation from a full quantitative spectral analysis, this finding agrees with the $0.2\,{\rm Fe}_\odot$ abundance measured in three IC1613 red supergiants by Tautvaišienė *et al.* (2007). With the oxygen abundances well established at $\sim 0.12\,{\rm O}_\odot$ from HII regions or $\sim$0.16$O_\odot$ from B-supergiants (Bresolin *et al.* 2007), IC1613's abundance ratio of α-element to iron may be sub-solar ([α/Fe] $= -0.1$ dex). Similar chemical mixtures have been found in other LG dwarf irregulars (Tautvaišienė *et al.* 2007; Hosek al. 2014). They are indicative of a tranquil recent star formation history with no major or violent episodes, and without a dominant population of massive stars at late times.

3. Discussion

The revision of the v_∞-v_{esc} dependence with the available data from the LG shows that this empirical relation suffers from such a large scatter that its use may be impractical. The scatter can be partly explained by the systematic uncertainties of the involved stellar properties, however we argue that part may be actually expected in the framework of RDW theory (see Garcia *et al.* 2014, for an extended discussion).

The terminal velocity is determined by the radiative acceleration at the outer wind layers, which is dominated by the strong resonance lines of a small number of light elements that still keep their ionization stage (Vink *et al.* 1999; Puls *et al.* 2000). Apparently subtle differences of [$T_{\rm eff}$,log g] between stars can lead to different local conditions and ionization equilibria in the outer wind that may alter v_∞. In this context v_∞/v_{esc} is not necessarily monotonic, and this translates into scatter in the v_∞/v_{esc} vs $T_{\rm eff}$ plot. Departures from solar chemical mixtures, unaccounted for when constructing the scaling relations of v_∞, may also add to the scatter.

The effect of non-solar chemical mixtures on RDWs has been scarcely studied in the literature. Besides terminal velocities, mass loss rates may also be affected. At solar-like metallicity, iron, with many optically thick lines in the wind, is the main driver of mass loss. At poorer metallicities the iron lines become optically thin while the strong resonance lines of CNO remain optically thick and may drive the wind (Vink *et al.* 2001; Krtička & Kubát 2014). Krtička & Kubát (2014) establish the separation of these two regimes at $Z \lesssim 0.1\,Z_\odot$. In other words: at the metallicity of IC1613, NGC3109 and WLM $\dot{M}$ and v_∞ (hence $D_{\rm mom}$) depend not only on the stellar luminosity and global metallicity, but also on detailed abundances.

These points suggest that wind properties should be studied on a star to star basis. Some groups have already taken on this approach and, instead of recipes, provide full wind simulations at several points of the [$T_{\rm eff}$,log g] parameter space of O-stars (e.g.

Muijres *et al.* 2012). If recipes and scaling relations are still to be used we should at least evolve into a two-parameter view of metal content, accounting separately for light elements and iron, especially at the $Z \lesssim 0.1\,Z_\odot$ regime. A view where α-elements and iron are considered separately, better represents the chemical evolution of galaxies. The effects of CNO processing should also be studied in detail.

4. Summary and conclusions

We present the first UV study of low-Z OB-stars beyond the SMC. Our results set an urgent reminder to three points:

• UV spectroscopy holds key information on the winds of OB stars that, if neglected, may lead to erroneous results.

• The v_∞/v_{esc} scaling relation suffers from large scatter. Terminal velocities obtained from this relation may be wrong by a factor of 2. Our results also call into question the dependence of v_∞ with one single global metallicity parameter.

• Oxygen is not a good proxy for metallicity, as the detailed abundance pattern of a galactic region depends on the star formation history of the galaxy.

These three points, long-known but overlooked because of feasibility issues, introduce large uncertainties in the WLR. The problem of low-Z OB stars with strong winds, established from optical spectroscopy only, might serve as illustration. We will provide further evidence on this topic with a joint optical+UV analysis of our IC1613 sample.

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Discussion

Nieva: Is there a way you can recognize spectroscopic binaries in your star sample?

García: For some stars we have multiple spectra and we can check for radial velocity variations. But mostly, the resolution is too low to recognize binaries. We do know that one of the sample stars is an eclipsing binary, found in a previous photometric survey by Alceste Bonanos.

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